

GRAVITATIONAL WAVE SIGNALS FROM THE COLLAPSE OF THE FIRST STARS

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ABSTRACT

We study the gravitational wave emission from the first stars which are assumed to be Very Massive Objects (VMOs). We take into account various feedback (both radiative and stellar) effects regulating the collapse of objects in the early universe and thus derive the VMO initial mass function and formation rate. If the final fate of VMOs is to collapse, leaving very massive black hole remnants, then the gravitational waves emitted during each collapse would be seen as a stochastic background. The predicted spectral strain amplitude in a critical density Cold Dark Matter universe peaks in the frequency range $\nu \approx 5 \times 10^{-4} - 5 \times 10^{-3}$ Hz where it has a value in the range $\approx 10^{-20} - 10^{-19}$ Hz^{-1/2}, and might be detected by *LISA*. The expected emission rate is roughly 4000 events/yr, resulting in a stationary, discrete sequence of bursts, *i.e.* a shot-noise signal.

Subject headings: galaxies: formation - intergalactic medium - gravitational waves - cosmology: theory

1. INTRODUCTION

Hierarchical models of cosmic structure formation predict that the first collapsed, luminous objects (often referred to as Pop III) should form at redshift $z \approx 30$ and have a total (*i.e.* dark + baryonic) mass $M \approx 10^6 M_\odot$ (Couchman & Rees 1986, Ciardi & Ferrara 1997, Haiman *et al.* 1997, Tegmark *et al.* 1997, Ferrara 1998, Ciardi *et al.* 1999 [CFGJ], Nishi & Susa 1999). These properties are typically derived by requiring that the cooling time, t_c , of the gas is shorter than the Hubble time, t_H , at the formation epoch, but as we will see later (see CFGJ for a thorough discussion) several feedback effects could modify this conclusion. Particularly important is the correct treatment of the molecular hydrogen formation/destruction network, this molecule being the only efficient coolant for objects close to the above mass scale.

As the collapse proceeds, the gas density increases and the first stars are likely to be formed. However, the final product of such star formation activity is presently quite unknown. This uncertainty largely depends on our persisting ignorance on the fragmentation process and on its relationship with the thermodynamical conditions of the gas. Ultimately, this prevents firm conclusions on the mass spectrum of the formed stars or their IMF to be drawn. In the last two decades this problem has been tackled intermittently (Silk 1977; Kashlinsky & Rees 1983; Palla, Salpeter & Stahler 1983; Carr *et al.* 1984, Carr 1994, Uehara *et al.* 1996, Omukai & Nishi 1998). These studies, however, could not converge to the same conclusion on the typical mass range of newly formed stars in the first protogalactic objects. Roughly speaking, two possibilities have been proposed: either (i) Very Massive Objects (VMOs), *i.e.*, single stars with mass in the range $10^2 - 10^5 M_\odot$ (or even larger) could be formed, or (ii) a

more common stellar cluster, slightly biased towards low-mass stars, would emerge (or some combination of the two involving low-mass star coalescence to form a VMO). Early studies (Fricke, 1973, El Eid *et al.* 1983; Ober *et al.* 1983) of the physics of VMOs were left almost unfollowed in the literature, probably because observational evidences of the VMO hypothesis were lacking in the local universe. The field has recently been rejuvenated by observations, as the Pistol Star (Figer *et al.* 1998) a VMO with mass $\simeq 250 M_\odot$ and about 1 Myr old, and calculations (collected in the review by Larson 1998) indicating that at earlier times the IMF was top-heavy and that VMOs could be a plausible outcome of the process. This possibility would bear tremendously important consequences for the reionization and metal enrichment of the intergalactic medium, as well as for galaxy formation and the nature of the dark matter.

We propose here a test of the VMO hypothesis based on the detection of the gravitational waves (GW) emitted during the collapse into very massive black holes in the late phases of their evolution. The extreme assumption is made that the stellar population of Pop III objects is entirely made of VMOs with mass proportional to their parent object. This allows to estimate an upper limit to the cumulative GW signal from VMOs and to compare it with existing or forthcoming experimental apparatus (VIRGO, LIGO, LISA). This proposal is an ideal development of the original suggestion by Thorne (1978) and Carr, Bond & Arnett (1984) made possible by an improved understanding of structure formation, properties of early objects and their GW emission mechanisms. The method adopted here presents some similarities to the one outlined in Ferrari, Matarrese & Schneider (1999), although that work concentrated on the stochastic GW background produced by the core-collapse of standard supernovae at relatively low redshift.

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2. THE FIRST STARS

The gas in a forming galaxy is initially virialized in the potential well of the parent dark matter halo and ignition of star formation is possible only if the gas can efficiently cool and loose pressure support. For a plasma of primordial composition at temperature $T < 10^4$ K, the typical virial temperature of the early bound structures, molecular hydrogen is the only efficient coolant. Thus, a minimum H_2 fraction $f_{H_2}^{min} \approx 5 \times 10^{-4}$ is required for the gas to cool (Tegmark *et al.* 1997). As this value is typically more than 100 times the intergalactic relic H_2 abundance, it is necessary to study in detail the H_2 formation efficiency during the collapse phase. The condition $f_{H_2} > f_{H_2}^{min}$ is met only by relatively large halos implying that for each virialization redshift there will exist some critical, redshift dependent mass, M_{crit} , such that only protogalaxies with total mass $M > M_{crit}$ can eventually form stars. We can then associate to each Pop III object with $M > M_{crit}$, a corresponding baryonic collapsed mass equal to $M_b = \Omega_b M$. Throughout the paper we adopt a value of the baryon density parameter $\Omega_b = 0.06$.

However, this is only half of the story. In fact, photons from the first stars with energies in the Lyman-Werner band and above the Lyman limit, respectively, can photodissociate H_2 molecules and ionize H and He atoms in the surrounding IGM. This is the so-called *radiative feedback* which suppresses the formation of objects more massive than M_{crit} but with mass below M_{sh} . The latter mass scale corresponds to the minimum total mass required for an object to self-shield from an external flux of intensity $J_{s,0}$ at the Lyman limit. The dissociating flux is the sum of two separate contributions: the first is coming from the background radiation produced by all luminous sources at a given redshift; the second comes instead from the direct flux of neighbor objects. The relative importance of the two depends on cosmic epoch. The detailed calculation of M_{sh} is rather complicated but it is fully described in CFGJ; hence we do not repeat it here. Proto-galaxies with virial temperatures $T_{vir} \gtrsim T_H = 10^4$ K, corresponding to a mass $M_H = 4.4 \times 10^9 M_\odot (1 + z_{vir})^{-1.5} h^{-1}$, where z_{vir} is the redshift of virialization, for which cooling via Ly α line radiation is possible are not affected by the radiative feedback and are assumed to form stars unimpeded. These results are graphically shown in Fig. 1. For example, at $z \approx 15$, it is $6 \times 10^6 M_\odot \approx M_{crit} < M_{sh} < M_H \approx 10^8 M_\odot$, depending on the value of $J_{s,0}$.

However, those results should be applied with a caveat to the presently analyzed situation in which the luminosity in the early universe - and hence the radiative feedback - is dominated by VMOs rather than by standard stars with a Salpeter IMF as assumed by CFGJ. The main problem is that the emission spectrum of VMOs is not known (although it is currently under investigation [Chiosi, private communication]) and therefore the feedback effect cannot be calculated entirely self-consistently. To alleviate the problem, though, we note that CFGJ concluded that the results are poorly sensitive to the exact form of the spectrum as long as it is of a soft, stellar type.

In Fig. 2 we show the evolution of the VMO initial mass function, $\Phi(M, z)$, deduced from the simulations by CFGJ in which all above effects have been included, for three different redshifts. These results have been obtained

for a critical density Cold Dark Matter (CDM) model ($\Omega_0=1$, $h=0.5$ with $\sigma_8=0.6$ at $z=0$); as a consequence all the results presented here refer to the same cosmological model. The mass of the VMO is here determined as $M_{VMO} = f_{b*} M_b$, with a baryon-to-star efficiency conversion $f_{b*} = 0.012$. As expected the mass distribution shifts towards larger masses with time, but smaller masses cannot form because of the collapse conditions imposed. Together with the VMO IMF, we can directly calculate their formation rate from the curves given in Fig. 11 of CFGJ which we do not repeat here.

A great deal of uncertainty obviously remains on the upper mass limit of VMOs. As the mass of the parent Pop III object becomes larger, it is increasingly difficult for the gas to collapse preventing fragmentation into lower mass stars (see however Silk & Rees 1998). Nevertheless, conditions could be suitable for the steady growth of a massive star through collisions with other intermediate mass stars. There is now substantial amount of theoretical work on this subject, mostly for the formation of relatively massive stars ($M > 100 M_\odot$) in the local universe and neglecting the effects of a massive dark matter halo as the one in which Pop III objects are embedded (Bonnell, Bate & Zinnecker 1998, Portegies Zwart *et al.* 1999). The central VMO in the Pop III cluster is then “rejuvenated” by each new collision, and its lifetime is extended considerably as a consequence. When does this VMO mass build-up process come to an end? The usual argument based on the idea that radiation pressure from the VMO finally removes the gas producing the cluster expansion with consequent decrease of the stellar collision rate is probably not appropriate in this context as the gravitational field (dominated by the dark halo) would be only very weakly affected. Also, radiation pressure might have been much less important in the absence of heavy elements.

What are the possible fates of VMOs? The answer depends essentially on their mass. Here we are interested in objects with $10^3 M_\odot \lesssim M_{VMO} \lesssim 10^7 M_\odot$, *i.e.* the span of the IMF in Fig. 2. Stars more massive than about $100 M_\odot$ are pair-production unstable (Fowler & Hoyle 1964). This process may lead to (Portinari *et al.* 1998) *i)* violent pulsation instability with final iron core instability, *ii)* complete thermonuclear explosion, or *iii)* collapse to a black hole. Case *iii)*, the one of interest here, occurs for masses $M \gtrsim 200 M_\odot$ (but rotation might increase this value, Glatzel *et al.* 1985). At higher masses ($M \gtrsim 10^5 M_\odot$) the evolution depends on metallicity, Z (Fricke 1973, Fuller *et al.* 1986): if $Z \lesssim 0.005$ the star collapses to a black hole due to post-Newtonian instabilities without ignition of the hydrogen burning; for higher metallicities it explodes since it could generate nuclear energy more rapidly from the β -limited cycle. The former case appears to be appropriate here, as the metallicity level produced by reionization is only $Z \approx 6 \times 10^{-6}$ (CFGJ), and likely to be even smaller if the nucleosynthetic products are swallowed by black holes. These conclusions are based on the detailed simulations by Fuller *et al.* (1986) which extend up to stellar masses $M = 10^6 M_\odot$. It has to be pointed out that if some fraction of dark matter is present (at the level of about 0.1%-1% of the VMO central density), the onset of post-Newtonian instability can be delayed and the hydrogen burning ignited; however, this *fa-*

vers the collapse to a black hole rather than the explosion, as shown by McLaughlin & Fuller (1996). Above $10^6 M_\odot$ the study is tremendously complicated by the necessity of taking into account general relativity effects which can influence the stability and evolution of these stars. Little is known about supermassive objects although promising investigations are underway (Baumgarte & Shapiro 1999, Baumgarte, Shapiro & Shibata 1999). In order not to add additional uncertainty sources to our calculation *our main results are limited to VMOs with $M \leq 10^6 M_\odot$* . However, because of the interesting nature of these objects based on the preliminary findings of Baumgarte & Shapiro (1999), we will also discuss separately the GW signal produced by the largest objects present in the derived VMO IMF.

3. GW EMISSION FROM VMBH COLLAPSE

The properties of the gravitational radiation emitted during the stellar collapse to a black hole have been extensively investigated during the past 20 years (see Ferrari & Palomba 1998 for a recent review). The gravitational energy is released in a short initial broad-band burst with efficiency ϵ_g so that the total gravitational energy emitted is $\epsilon_g M_B c^2$, where M_B is the mass of the newly formed hole (Thorne 1986). The values of ϵ_g found both in perturbative approaches and in fully numerical simulations came out quite low. For an axisymmetric collapse, the efficiency is less than $\sim 7 \times 10^{-4}$ (Stark & Piran 1985). However, if the star is rotating sufficiently rapidly to undergo a dynamical bar mode instability prior to forming the black hole, then the energy released in gravitational waves can be substantially higher (Smith, Houser & Centrella 1995). Therefore, the collapse of a VMO promises to be a very interesting source for gravitational wave detection.

For the sake of simplicity, we assume that the gravitational energy released during each collapse, $\Delta E_g = \epsilon_g M_B c^2$, is emitted in a broad-band burst centered at a frequency, $\nu_0 = c/10R_g$, which corresponds to a wavelength of order 10 times the Schwarzschild radius, $R_g = 2GM_B/c^2$, associated to the hole (Thorne 1978, Carr, Bond & Arnett 1984). The spectrum of gravitational waves emitted during the collapse can be approximated to a Lorentzian,

$$\frac{dE}{d\nu} = \frac{\Delta E_g}{\nu_0 \mathcal{N}} \frac{\nu^2}{(\nu - \nu_0)^2 + \Gamma^2} \quad (1)$$

where $\Gamma = (2\pi\Delta t)^{-1}$, $\Delta t = 1/\nu_0$ is the typical duration of the burst, $\nu_0 \mathcal{N}$ is the normalization,

$$\nu_0 \mathcal{N} = \int_0^{\nu_{max}/\nu_0} d\tilde{\nu} \frac{\tilde{\nu}^2}{(1 - \tilde{\nu})^2 + 0.03}$$

with $\tilde{\nu} = \nu/\nu_0$ and $\nu_{max} = c/R_g$ the maximum frequency emitted by the source. While the available theoretical waveforms are too uncertain to warrant a more elaborate analysis, this crude approximation well highlights the main features and assumptions of the model.

The average gravitational flux emitted by a source at a distance r can be easily shown to be,

$$\langle \frac{dE}{d\Sigma d\nu} \rangle = \frac{1}{4\pi r^2} \int d\Omega \left[\frac{dE}{d\Omega d\nu} \right] = \frac{1}{4\pi r^2} \frac{dE}{d\nu}. \quad (2)$$

For sources at cosmological distances, the above expression can be immediately generalized to,

$$\langle \frac{dE}{d\Sigma d\nu} \rangle = \frac{(1+z)^2}{4\pi d_L(z)^2} \frac{dE_e[\nu(1+z)]}{d\nu_e}, \quad (3)$$

where $\nu = \nu_e(1+z)^{-1}$ is the redshifted emission frequency, ν_e , and $d_L(z)$ is the luminosity distance to the source.

4. PREDICTIONS AND IMPLICATIONS

If the final fate of VMOs is to collapse, leaving very massive black hole (VMBH) remnants, then the overall effect of the gravitational waves emitted during each collapse would be seen today as a stochastic background. The signal produced by these events can be computed integrating the gravitational signal contributed by each source over the differential source formation rate,

$$\frac{dE}{d\Sigma d\nu dt}[\nu] = \int \int dz dM \Phi(M, z) \frac{\dot{\rho}(z)}{(1+z)} \langle \frac{dE}{d\Sigma d\nu} \rangle \frac{dV}{dz}, \quad (4)$$

where $\dot{\rho}(z)/(1+z)$ is the VMO cosmic formation rate per comoving volume obtained from the CFGJ simulations.

The spectral energy density allows the evaluation of the corresponding spectral strain amplitude,

$$S_h[\nu] = \frac{2G}{\pi c^3} \frac{1}{\nu^2} \frac{dE}{d\Sigma d\nu dt}[\nu]. \quad (5)$$

Clearly, the relevant parameters which determine the amplitude and the location of the signal are the efficiency ϵ_g and the fraction of the initial mass which participates to the collapse, $\phi_B = M_B/M$. The value of ϕ_B , as well as its dependence on M , is very uncertain. For an axisymmetric collapse, only about 10% of the initial stellar mass collapses to the final black hole (Stark & Piran 1985). However, Baumgarte & Shapiro (1999) suggest that for $M \gtrsim 10^6 M_\odot$, only a few percent of the initial mass is left outside of the black hole, most likely in the form of a disk. Thus, it is not unreasonable to assume that ϕ_B may vary in the range 0.1-0.9 (see also Carr, Bond & Arnett 1984).

The stochastic background signal predicted by our model is shown in Fig. 3 for $\epsilon_g = 10^{-4}$ and $\phi_B = 0.1$. There we compare the spectral energy density produced by pre-galactic VMBHs to the more recent contribution from core-collapse SNe at $z < 6$ (see Ferrari, Matarrese & Schneider 1999). Due to their larger masses, the gravitational signal from the birth of VMBHs falls at much shorter wavelengths than that produced by core-collapse SNe.

In spite of their great distances, pre-galactic VMOs produce a background signal which adds, as a confusion noise component, to the *LISA* sensitivity curve in the range $10^{-3} - 10^{-2}$ Hz (see Fig. 4), for the parameters assumed in the model. Thus, we expect that *LISA* will be able to place an upper limit on the intensity of the Pop III background signal in this frequency range.

4.1. Contribution from Supermassive Objects

In Fig. 3 we also show a crude estimate of the signal produced by VMOs with masses $\gtrsim 10^6 M_\odot$ which undergo a dynamical bar instability before the final implosion. This possibility has been recently discussed by Baumgarte &

Shapiro (1999). They investigated the secular evolution of supermassive stars (SMSs) with masses $\gtrsim 10^6 M_\odot$, up to the onset of the instability. The gravitational efficiency of the collapse as well as the detailed waveforms of the resulting signal can be definitely assessed only with a numerical, three-dimensional hydrodynamics simulation in general relativity (Baumgarte, Shapiro & Shibata 1999). However, based on simple arguments, these authors suggest that the collapsing star may form a nonaxisymmetric bar before it forms a black hole.

Numerical simulations of the dynamical bar mode instability in compact stellar cores with stiff equation of state ($n < 1.5$) have shown that a burst of gravitational radiation is emitted with an efficiency ϵ_g ranging between 10^{-4} and 10^{-2} , depending on the initial equatorial radius of the bar, R_{eq} , and on the polytropic index (Houser & Centrella 1996). The burst is centered at a frequency $\sim 2\nu_{bar}$, where ν_{bar} is the rotation frequency of the bar,

$$\nu_{bar} = \frac{1}{2\pi} \left(\frac{GM}{R_{eq}^3} \right)^{1/2}.$$

The width of the gravitational burst depends sensitively on the polytropic index: stiffer models undergo several episodes of bar formation and recontraction, emitting a sequence of bursts of decreasing amplitude. The structure of SMSs with $M \gtrsim 10^6 M_\odot$ is that of an $n = 3$ polytrope (Baumgarte & Shapiro 1999) and it is reasonable to assume that the radiation emitted would be concentrated in a single burst of width $\sim 2\nu_{bar}$. Following Baumgarte & Shapiro (1999) we assume,

$$R_{eq} \sim 1.5 R_{pol} \quad R_{pol} \sim \frac{15GM}{c^2}$$

where R_{pol} is the polar radius at the onset of the bar instability. With these parameters, we model the spectrum emitted by a VMO with $M > 10^6 M_\odot$ using eqs. (1) and (3) with an efficiency $\epsilon_g = 10^{-4}$ and $\phi_B = 0.1$.

As it can be seen from Fig. 3, these objects produce a significant signal at frequencies $< 10^{-4}$ Hz, too small to be detectable with *LISA*.

4.2. Rates and Duty Cycle

The rate of VMBH formation is shown in Fig. 5 as a function of redshift. The total number of VMBHs formed per unit time is $N_{VMBH} \sim 4000$ events/yr. The ratio of the duration of each burst to the separation between successive bursts, i.e. the duty cycle,

$$\frac{dDC[z]}{dz} = \frac{\dot{\rho}(z)}{(1+z)} \frac{dV}{dz} \frac{(1+z)}{v_0} \int dM \Phi(M, z) \quad (6)$$

is also shown in Fig. 5 as a function of z . It is clear that the overlap condition, $DC > 1$, is not satisfied even if we consider all VMOs out to the farthest z . Thus, we find, contrary to previous claims (Carr, Bond & Arnett 1984), that VMBHs that originate from Pop III stars do not generate an overlapping background but rather a stationary, discrete sequence of bursts, i.e. a shot-noise signal (see also Ferrari, Matarrese & Schneider 1999).

Thus, though a stochastic background at comparable frequencies and amplitude might have been generated in

the very early universe, it would still be possible to disentangle any Pop III gravitational signature through this peculiar shot-noise character.

5. SUMMARY AND DISCUSSION

We have investigated the gravitational wave emission from the collapse of Very Massive Objects formed in the early universe. The presence of such objects would bear tremendously important consequences for the intergalactic medium reionization, the generation of the first metals and for their contribution to the dark matter in the universe.

The predicted spectral strain amplitude in a critical density CDM universe peaks in the frequency range $\nu \approx 5 \times 10^{-4} - 5 \times 10^{-3}$ Hz where it has a value in the range $\approx 10^{-20} - 10^{-19}$ Hz $^{-1/2}$, which is above the *LISA* sensitivity curve. The expected emission event rate is roughly 4000 events/yr, resulting in a stationary, discrete sequence of bursts, i.e. a shot-noise signal. The issue of the actual detectability of our signal by *LISA* is more complex, as cross-correlation techniques, which would be needed to disentangle a stochastic background from the noise, cannot be applied here (see, e.g. Flanagan & Hughes 1998). So, any background would actually add as a confusion limited noise component to the *LISA* instrumental noise. In this sense *LISA* will place an upper limit to the amplitude of our signal. On the other hand, the predicted stochastic background has a shot-noise structure, similarly to the background produced, in the high frequency bandwidth, by the core-collapse to black holes in standard supernovae at $z \lesssim 6$ (Ferrari, Matarrese & Schneider 1999, see Fig. 3).

Thus, standard detection techniques, which have been developed for continuous stochastic signals, can be applied only if the integration time of the antenna is much longer than the typical separation between two successive bursts (of the order of a few hours for the present study).

Specific techniques should be investigated in order to assess how far the shot-noise structure can be exploited to help the detection or, at least, to distinguish the signal from the instrumental noise or from continuous backgrounds contributing in the same band.

Our underlying assumption that down to $z \approx 10$ fragmentation in collapsing cosmological objects is inhibited by the absence of metals (and therefore only very massive stars are formed) is clearly strong and, at present, untestable, but yet not an unreasonable one. Its motivation is that it allows to estimate an upper limit to the expected gravitational wave emission from this population of astrophysical objects. The growth of the metallicity level in the universe not only favors fragmentation of the gas, but also quenches the formation of VMBHs as these objects tend to explode, as discussed in Sec. 2. For these reasons, the GW contribution from collapsing VMOs can only come from redshifts higher than approximately 10.

Some details of the calculation are uncertain, as for example the exact shape of the GW emission spectrum from a collapsing VMO. However, a different choice of the spectrum (i.e. the one suggested by Stark & Piran 1985) produces only a slight difference in the integrated spectral energy distribution. Indeed, the expected signal could be even higher than what predicted here if the conversion efficiency of the total gravitational energy into GWs is higher than the value 10^{-4} used here, as suggested by some pre-

vious studies (the amplitude of the GW signal is $\propto \epsilon_g$).

Detecting a GW signal from VMOs will become possible with the new class of GW detectors as *LISA*, according to our predictions. This would allow to directly test epochs and objects which would be otherwise difficult to reach with other instruments, at best for a very long time. This experiment could also provide stringent limits to the cosmic star formation history at redshifts $z > 10$ and to investigate the physics and properties of the first stars in the universe. The remnants of such primordial objects could still be present in halos of galaxies like our own (for an excellent review see Carr 1994). The type of BH remnants discussed here are interesting dark matter candidates: gravitational lensing effects measured from the line-to-continuum variation of quasars suggest that the

lensing objects in the intervening galaxies have a mass in the range $3 \times 10^4 - 3 \times 10^7 M_\odot$ (Subramanian & Chitre 1987). However, the upper end of this interval might be constrained to be $\lesssim 10^6$ by either dynamical (heating of disk stars, Lacey & Ostriker 1985) or luminosity (accretion of gas in the halos of galaxies, Ipser & Price 1977; Hegyi *et al.* 1986) constraints. Interestingly enough, this interval appears not only to well match the predicted VMO IMF (see Fig. 2), but also to provide a GW signal which might be detectable by *LISA*.

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REFERENCES

- Baumgarte, T. W., Shapiro, S. L., 1999, to appear in ApJ
 Baumgarte, T. W., Shapiro, S. L. & Shibata, M., 1999, in preparation
 Bender, P. L. & Hils, D., 1997, Class. Quantum Grav., 14, 1439
 Bonnell, I., Bate, M. & Zinnecker, H. 1998, MNRAS, 298, 93
 Carr, B., Bond, J. R. & Arnett, W. D. 1984, ApJ, 277, 445
 Carr, B. 1994, ARA&A, 32, 531
 Ciardi, B. & Ferrara, A. 1997, ApJ, 483, 5L
 Ciardi, B., Ferrara, A., Governato, F. & Jenkins, A. 1999, preprint (astro-ph/9907189,CFGJ)
 Couchman, H. M. P. & Rees, M. J., 1986, MNRAS, 221, 53
 El Eid, M.F., Fricke, K. J., Ober, W. W., 1983, A&A, 119, 54
 Ferrara, A. 1998, ApJ, 499, L17.
 Ferrari, V., Palomba, C., 1998, Int. J. Mod. Phys. D, 6, 825
 Ferrari, V., Matarrese, S. & Schneider, R. 1999, MNRAS, 303, 247
 Figer, D. F., Najarro, F., Morris, M., McLean, I. S., Geballe, T. R., Ghez, A. M. & Langer, N. 1998, ApJ, 506, 384
 Flanagan, E. E. & Hughes, S. A., 1998, Phys. Rev. D 57, 4535
 Fowler, W. A. & Hoyle, F. 1964, ApJS, 9, 201
 Fowler, W. A. 1966, ApJ, 144, 160
 Fricke, K. J. 1973, ApJ, 183, 941
 Fuller, G. M., Woosley, S. E. & Weaver, T. A. 1986, ApJ, 307, 675
 Glatzel, W., El Eid, M. F. & Fricke, K. J. 1985, A&A, 149, 419
 Haiman, Z., Rees, M. J., & Loeb, A. 1997, ApJ, 484, 985
 Hegyi, D. J., Kolb, E. W. & Olive, K. A. 1986, ApJ, 300, 492
 Houser, J. L. & Centrella, J. M., 1996, Phys. Rev. D54, 7278
 Ipser, J. R. & Price, R. H. 1977, ApJ, 216, 578
 Kashlinsky, A. & Rees, M. J. 1983, 205, 955
 Lacey, C. G. & Ostriker, J. P. 1985, ApJ, 299, 633
 Larson, R. B. 1998, preprint (astro-ph/9808145).
 McLaughlin, G. C. & G. M. Fuller, 1996, ApJ, 456, 71
 Nishi, R. & Susa, H. 1999, preprint
 Ober, W. W., El Eid, M.F., Fricke, K. J., 1983, A&A, 119, 61
 Omukai, K., & Nishi, R. 1998, ApJ, 508, 141
 Palla, F., Salpeter, E. E. & Stahler, S. W. 1983, ApJ, 271, 632
 Portegies Zwart, S. F., Makino, J., McMillan, S. L. W. & Hut, P. 1999, A&A, 348, 117
 Portinari, L., Chiosi, C. & Bressan, A. 1998, A&A, 334, 505
 Schneider, R., Ferrari, V., Matarrese, S. & Portegies Zwart, S. F., 1999, in preparation
 Silk, J. 1977, ApJ, 211, 638
 Silk, J. & Rees, M. 1998, A&A, 331, 1
 Stark, R. F. & Piran, T., 1985, Phys. Rev. Lett., 55, 891
 Subramanian, K. & Chitre, S. M. 1987, ApJ, 313, 13
 Tegmark, M., Silk, J., Rees, M.J., Blanchard, A., Abel, T. & Palla, F. 1997, ApJ, 474, 1
 Thorne, K. S., 1978, in Theoretical Principles in Astrophysics and Relativity, eds. N.R. Lebowitz, W.H. Reid and P.O. Vandervoort, (Chicago: UniPress)
 Thorne, K. S., 1986, in 300 Years of Gravitation, eds S. Hawking, W. Israel, Cambridge University Press, Cambridge
 Uehara, H., Susa, H., Nishi, R., Yamada, M. & Nakamura, 1996, ApJ, 473, L95

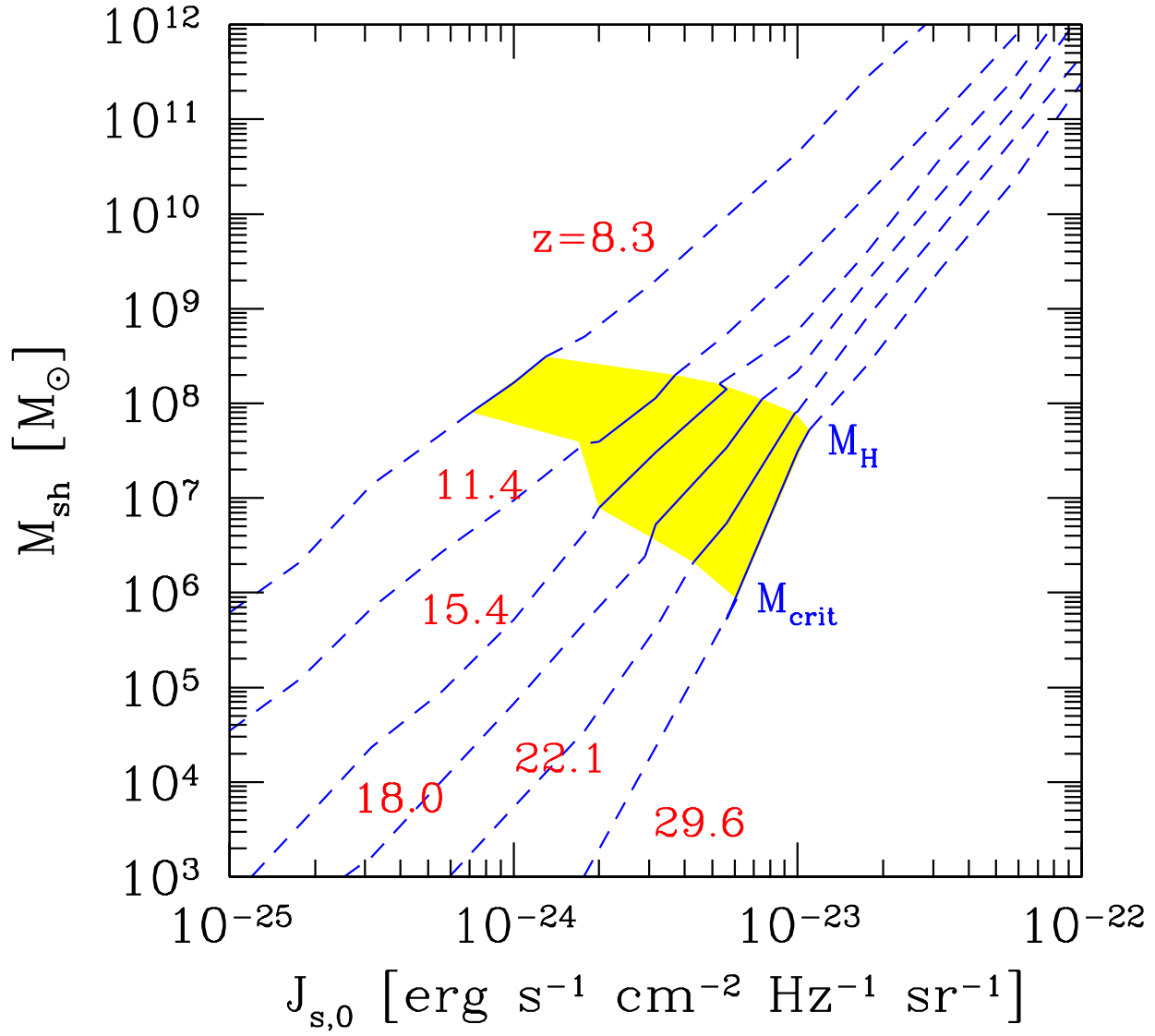


Fig. 1.— Minimum total mass for self-shielding from an external incident flux with intensity $J_{s,0}$ at the Lyman limit. The curves are for different redshift: from the top to the bottom $z = 8.3, 11.4, 15.4, 18.0, 22.1, 29.6$. Radiative feedback works in the shaded area delimited by the mass scales M_H and M_{crit} (see text).

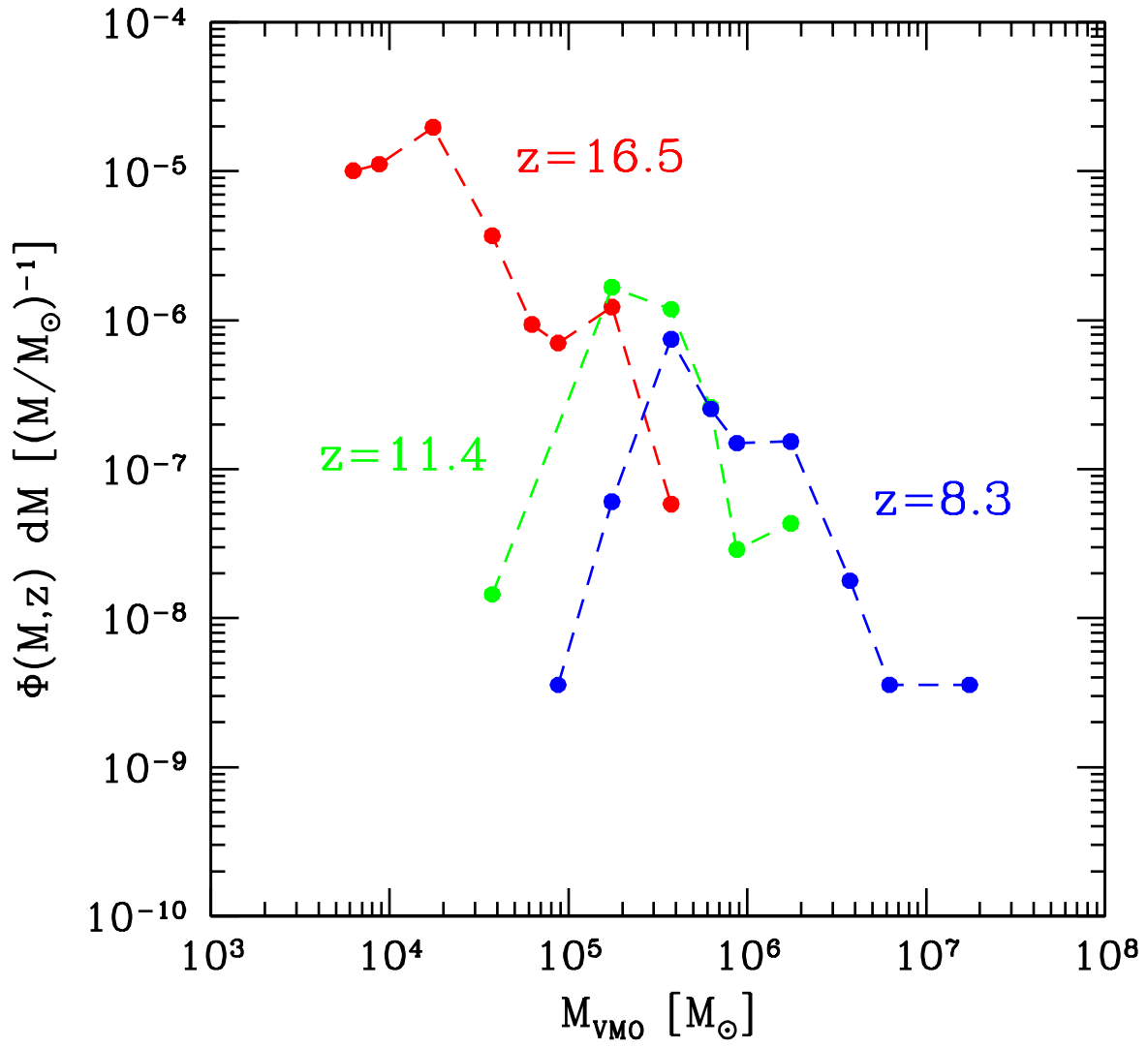


Fig. 2.— VMO initial mass function evolution at the three different redshifts $z = 16.5, 11.4, 8.3$.

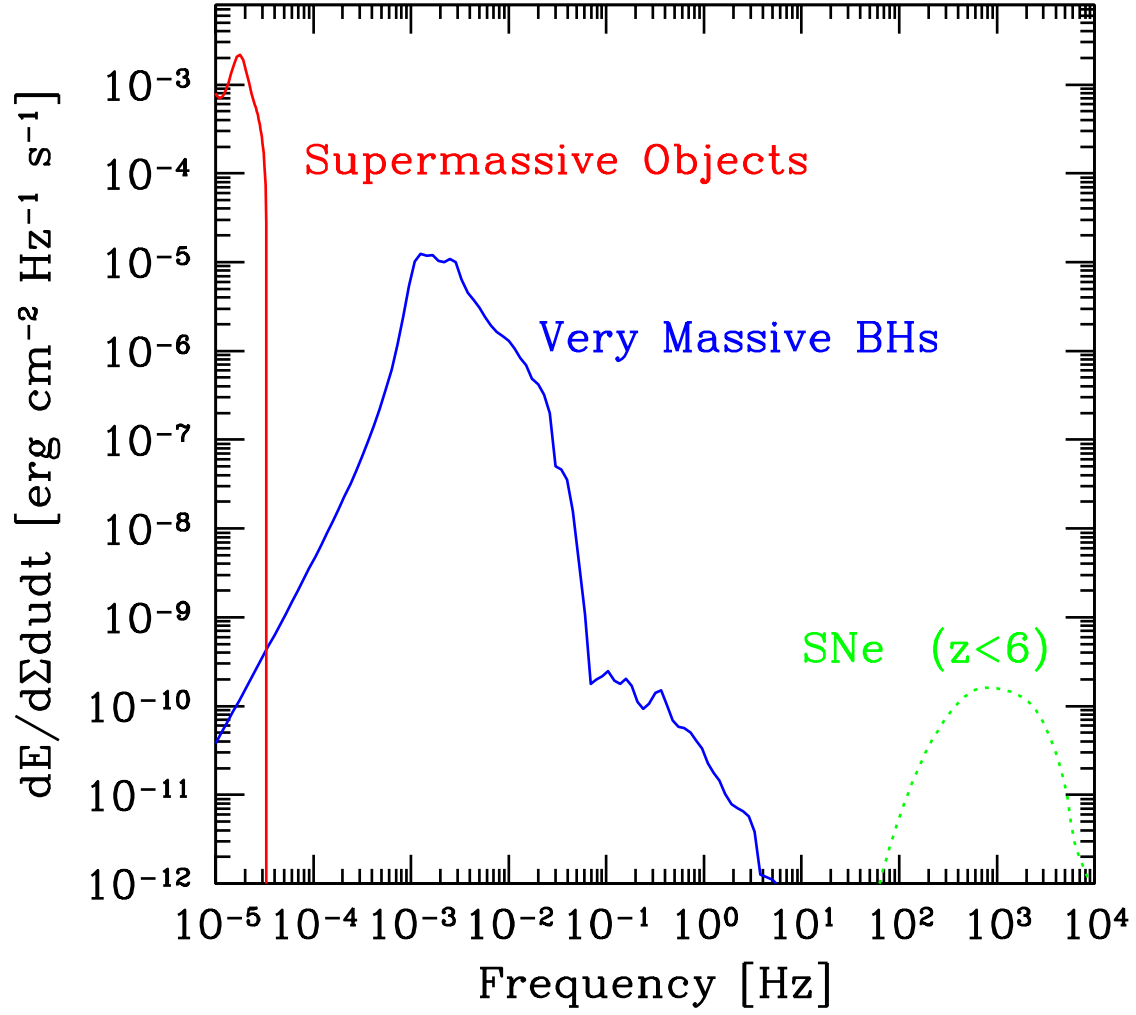


Fig. 3.— Stochastic background signal produced by the VMBHs remnants of PopIII stars and by core-collapse SNe leaving black hole remnants at $z < 6$. The background signal produced by VMBHs is computed assuming $\epsilon_g = 10^{-4}$ and $\phi_B = 0.1$ (see text). Also shown is the contribution from the collapse of supermassive ($M \gtrsim 10^6 M_\odot$) objects.

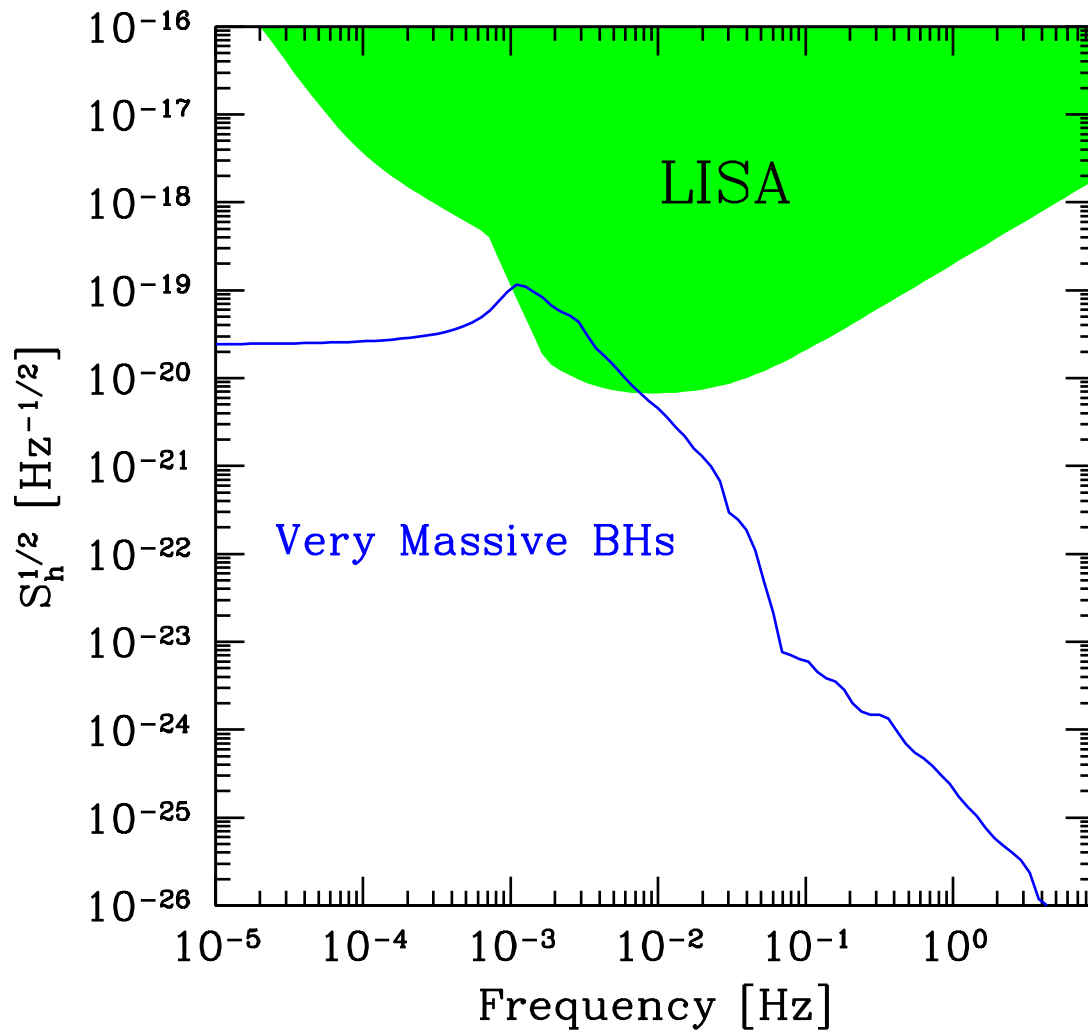


Fig. 4.— The spectral strain amplitude of the PopIII stars signal (assuming $\epsilon_g = 10^{-4}$ and $\phi_B = 0.1$) is compared to the sensitivity curve of the *LISA* space interferometer. The *LISA* sensitivity curve accounts for both the instrumental noise component and for the confusion noise component due to double white dwarfs binaries (Bender & Hils 1997).

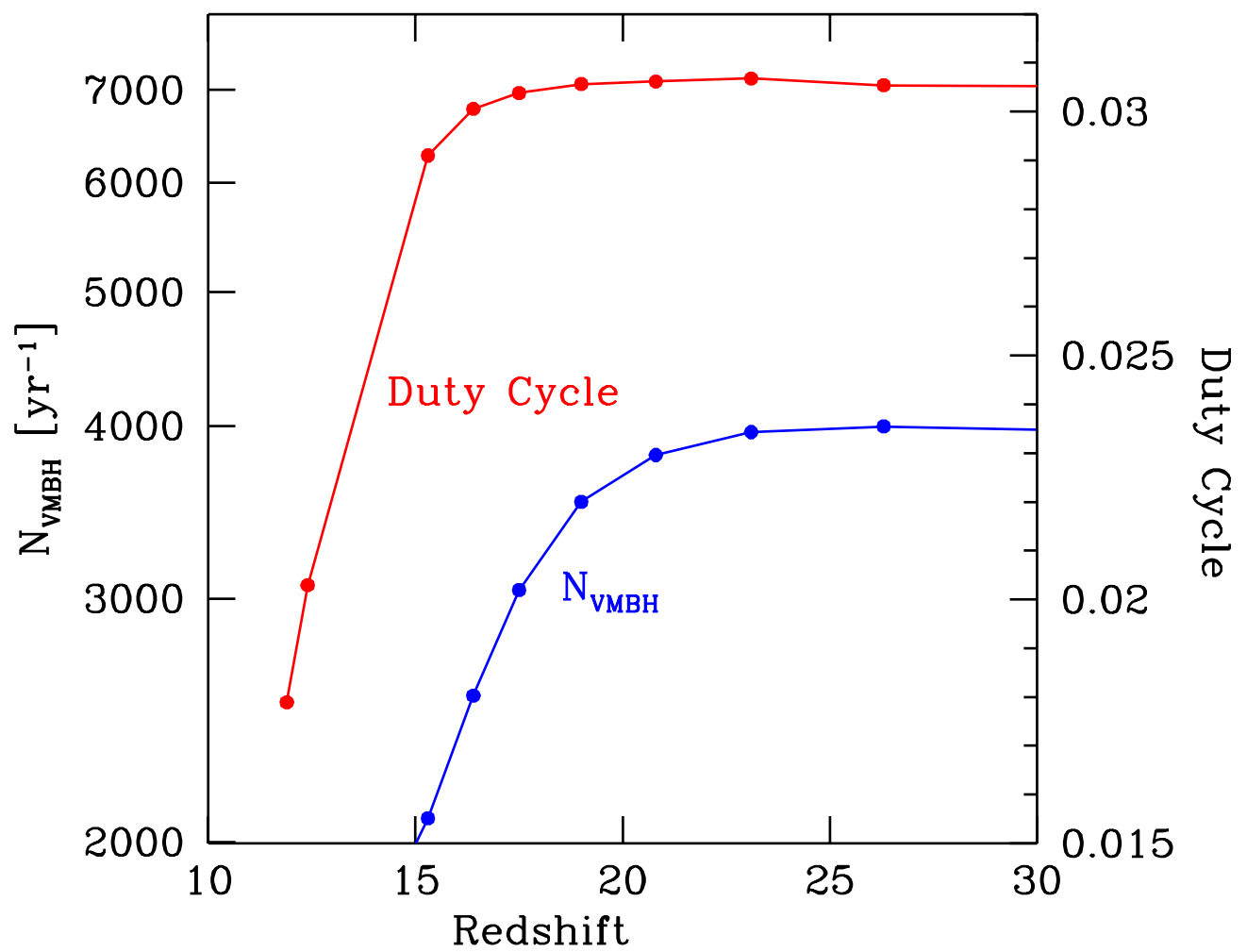


Fig. 5.— Rate of VMBH formation and duty cycle of the gravitational-wave signal produced by VMBH collapses as a function of redshift.